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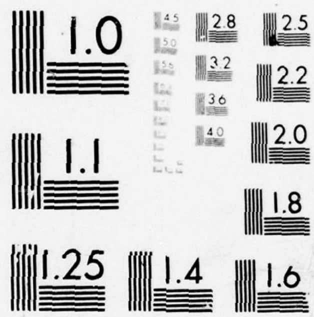

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SCATTER PROPERTIES OF MLD MIRRORS

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SCATTER PROPERTIES OF MLD MIRRORS

Abstract: A study and development of data processing techniques for spatial scatter intensity data from a MLD mirror was undertaken. Several processing schemes were investigated with the result that processing the data so as to produce a true and scaled polar plot of the scatter field seems to be the optimum way of displaying the information.

Studies of the scatter field of a particular MLD mirror did not support the notion that lobes are to be found in the pattern. On the contrary, the scatter field is more accurately described as a random spatial function. In addition, studies of the processed data patterns suggests that a possible measure of mirror quality may be had by direct comparison of its forward and back scatter characteristics.

SCATTER PROPERTIES OF MLD MIRRORS

Introduction: During the summer of 1977 a Dynamic Scatterometer was designed and constructed in the Avionics laboratory at Wright-Patterson Air Force Base (WPAFB) in Dayton, Ohio. (The details of this effort can be found in: Boehm, T. Joe, Scatter Studies on MLD Mirrors, Final Report United States Air Force, Office of Scientific Research, 19 August 1977). The purpose of this scatterometer is to be able to measure and record the scatter field intensity of a mirror in the region between an incident and reflected beam of light produced by a low power He-Ne laser. Although the basic mechanical construction of the scatterometer was completed by the end of the 1977 summer, a need to evaluate its performance and to develop techniques for mass data acquisition along with evaluation existed. This report is the result of a coordinated research effort,conducted the following summer (1978), aimed at eliminating these needs. In particular, the following two general areas are herein addressed:

1) Methodology and techniques associated with data acquisition, processing and interpretation.
2) Experimental results associated with the scatter field from a particular MLD (multi-layered-dielectric) mirror.

As can be noted, the two areas here are somewhat distinct and as such they will be treated separately in this report.

(I) Data Acquisition and Processing

To determine the optimum method of acquiring and processing the scatter data, several data sets were investigated. This data was recorded over the summer of 1978 at WPAFB by personnel in the avionics laboratory. The only significant change in the scatterometer over that described in the 1977 report was that the "detector assembly" was replaced by a commercially supplied photometer. (SPECTRA, Pritchard Photometer, Model 1980A). This instrument not only solved some of the earlier sensitivity and alignment problems but also provided an analog output of the point scatter intensity which formed the basis for this study. Scatter measurements were made on two different MLD mirrors. For each mirror, the following measurements were taken:

a) multiple data runs with the point and angle of incidence fixed.

b) changing the point of incidence and repeating (a) above.

Additionally, in the case of the second mirror at each point of incidence, scatter measurements were made with the angle of incidence set at 30 degrees and then repeated with the angle of incidence set at 45 degrees before moving to a new point of investigation on the mirrors surface.

Data Properties and Results: Each of the data runs produced an analog output which in turn had to be hand digitized in order to use high speed digital machines available and particularily adapted to processing data of this type. In each case auto-correlation and corresponding power spectrum were studied. Also, where applicable, cross-correlation between data sets was also investigated. These investigations produced the following results and conclusions:

1) The scatter field is highly repeatable if the point and angle of incidence remains invarient between sucessive data runs. This indicates that the field intensity is well above the ambient environmental noise and can therefore be directly measured without resorting to data stacking or other signal to noise enhancement techniques.

2) Repeatability is lost if the point of incidence is moved and then a return to the original point is attempted. Inadequate resolution in the positioning system seems to be indicated here.

3) Correlation and spectrum results indicate that the scatter intensities are random spatial functions in the region between the incident and reflected beam. This is contrary to the previously reported lobe pattern that preliminary tests seemed to indicate. It should however be pointed out that the lack of a definitive lobe pattern in these data runs does not exclude the theoretical possibility of their existance. The surfaces of the test mirrors chosen could be

irregular enough so that the random scatter totally obscures any such detail.

These results give to the following data processing conclusions. Since,to totally characterize the surface of a mirror requires such a large amount of data (a 10 mm square mirror measured to a surface resolution of 1 mm with a scatter angular resolution of 1 arc-min and for an incident angle resolution of 1 degree would produce approximately 32 million words of sampled data) a digital recording and processing scheme are required. Also, processing the data so as to provide a true polar plot of the scatter pattern from each data run appears to provide direct information on MLD mirror quality. Consequently, a computer program was written to process the data in this fashion.

Program Description: The data processing program was written in FORTRAN IV language compatible with the G-level compiler supplied by IBM for the IBM 360/50 digital computing system. FORTRAN was chosen primarily because it is a generally applicable language at most large computer installations and particularly so at WPAFB.

Each scatter data measurement produces what is called a data record. The digital representation, called a sampled data record, consists of an ordered sequence of numbers which contain the scatter information. For the purpose of describing the data processing program, each of these numbers or samples in this sequence will be given the symbol x_i with x_1 representing the first sampled data point, x_2 the second and so on.

Figure 1 shows in block diagram form the sequence of operations performed in processing a data record. It should be noted that the input data to this program is read from punched cards. This was done this way because this was the most practical way to encode the data produced by the scatterometer for this study. However, for general massive data acquisition routines, the punch card medium for data recording will probably be too slow and cumbersome to be practical. To illustrate, the previously described example, which give rise to approximately 32 million words of sampled data, would require slightly over 2 million cards or 200 cases (10000 cards/case) to properly record. Therefore, it is anticipated that in practice the program will read the input data from a mass data storage medium such as magnetic tape or magnetic disc or possibly directly from the scatterometer. In any case, the modification necessary to the program to accomdate these other modes of input is rather simple and should cause no problem.

Data Scaling: After the data along with the necessary control information is read, the first operation is a data scaling operation. Symbolically this operation may be represented as:

$$x_i \leftarrow K\, x_i$$

where

K is a constant

The $\leftarrow$ symbolizes a "redefining" type of operation. In the

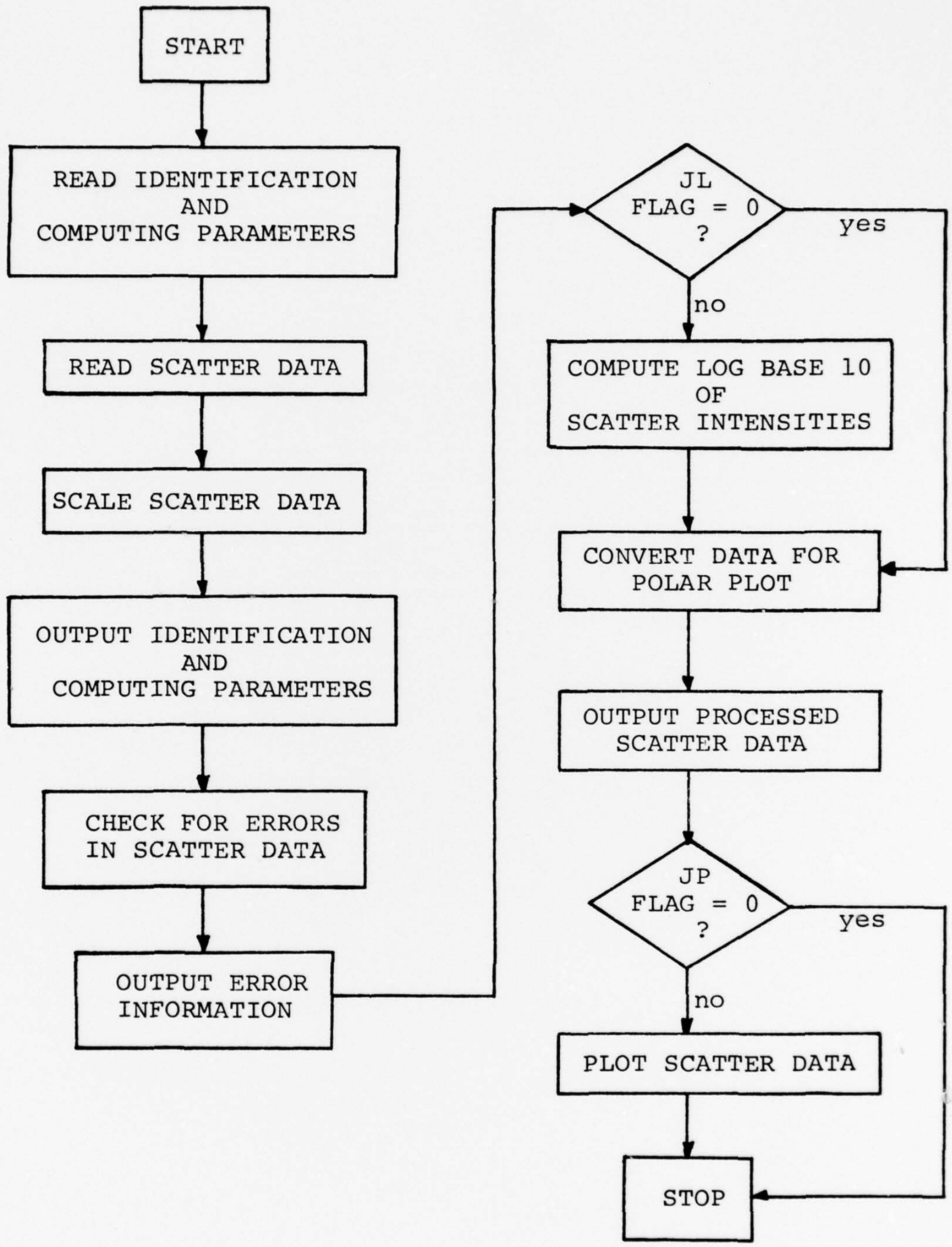

Figure 1. Block Diagram of Data Processing Sequence

above it is interpreted to mean that x_i is redefined to have the value resulting from the evaluation of the expression to the right of this symbol. Here x_i is seen to simply be multiplied by a constant. This scaling procedure is included in the program because it provides a way to allow the results of the overall processing to be directly comparable with previously processed data which may have been recorded under conditions of different sensitivity. Different recording sensitivities often arise because of system dynamic range considerations, system signal to noise properties, or just convenience.

Data Editing: The second computational step in the processing sequence is to edit each individual x_i. Each x_i value is checked to see if it falls within an allowable maximum and minimum. This maximum is dictated by constraints imposed by the experimental set-up. Also, the magnitude of each x_i is compared to that of the previous sample and checked to see whether a specified maximum for the difference between these two has been exceeded. This last check, for all practial purposes, amounts to checking the data to see if a specified maximum in the magnitude of the slope of the data has been exceeded. The reason for checking each data sample is that digital data acquisition systems quite often produce erroneous sample data values. These errors in data arise from occasional equipment malfunction and spurious system and environmental noise. When this happens, the error produced is usually of such magnitude that all of the above checks will not be satisfied. If a particular x_i is found not to satisfy these checks, it is "corrected" according to the following formula:

$$x_i = \frac{x_{i-1} + x_{i+1}}{2}$$

As can be seen, this is a simple linear interpolation correction. Three assumptions go with the use of the above formula. The first is that it yields the most probable value of x_i. The second is that the first and last value of x_i in the data record are correctly recorded. Third and finally, if x_i is in error, x_{i+1} and x_{i-1} are not. The first assumption is strictly satisfied only if the data record is a band limited Gaussian random function or a simple linear function. Never-the-less, a visual inspection of the effect on resulting scatter plots due to replacing a recorded value with its corresponding interpolated one showed the following: a) no detectable difference if the data involved did not under go a sign change in slope or b) barely preceptable variations in the corresponding scatter peak if it did. Assumptions two and three are mechanical and easy to check. These checks amount to visually inspecting the first and last data point of each record and having the computer print the value of the index "i" on all corrected points. If all the printed values of "i" differ from each other by at least two then the conditions imposed by the third assumption are satisfied.

Coordinate Conversion: The data record as originally recorded is in the polar-coordinate form. However if a true polar plot is desired, as is the case here, it is generally necessary to convert this data to its equivalent rectangular-coordinate form. This is the case because computer plotting facilities almost invariably utilize X-Y plotters which require the data to be in this form. The formulas used to make this conversion are:

$$Y_i = x_i \operatorname{Cos}(\phi_i)$$

$$X_i = x_i \operatorname{Sin}(\phi_i)$$

$$i = 1, 2, \cdot \cdot \cdot \cdot, N$$

where

Y_i and X_i are the corresponding X-Y coordinates,

ϕ_i is the angle associated with each x_i, and

N is equal to the number of sampled data points

In some cases it is more convenient to express the scatter data in a logarithmetic form. In fact this is usually the case because of the large dynamic range in intensity often encountered in scatter measurements. (Of the mirrors used in this study, variations approaching 5 orders of magnitude were observed.) The decision whether or not to make this conversion is determined by a control parameter defined each time the program is executed. If the decision is to logarithmetically convert the data, it is done for each data sample prior to the coordinate conversion routine and according to the following operation:

$$x_i \leftarrow \log_{10}(x_i)$$

Plot of Data: The final major processing step is to produce a polar plot of the processed scatter data. This is accomplished by a call to a subroutine written specifically for this purpose. This subroutine in turn utilizes three other subroutines. These will not be described here because they are:
a) rather straight forward and standard in form and
b) peculiar to the system interface in which they are utilized.
As a result the plot portion of the data processing program will have to be tailored to suit the requirements of the computational facility in which it is used.

Output: The output from the program is described below. The first output is basically information relating to mirror identification and the conditions under which the scatter data were acquired. Following the above is a summary of the error analysis. This includes a listing of the index associated with each data sample found to be in error, the value of that data sample, and the new value to which it was corrected. A count of the total number of data points found to be in error is also produced. This is followed by a complete listing of each processed data point in both it's polar and rectangular form. It is anticipated that this will need to be suppressed with large data sets or when processing becomes routine. The final output is in the form of a polar plot of the scatter data. The production of this plot is controlled by an input parameter defined each time the program is executed.

A complete FORTRAN listing of this program along with instructions for its use is included in the appendix of this report.

II Experimental Scatter Field Results

A MLD mirror identified by the "in-house" number of #449 was used to obtain comprehensive scatter field data. This mirror is a "max-flat" type with several dielectric layers designed for an incident beam angle of 30 degrees at a 632.8 nm wavelength. The dielectric layers were put down in the traditional several $\frac{1}{4}\lambda$ layers to each $\frac{1}{2}\lambda$ layer sequence. The exact physical details of the mirror and its structure are not of first order importance since the empirical character of the scatter field and the establishment of a data base were the prime objectives. To obtain the scatter data, the following procedure was adopted. An arbitrary point of incidence was selected on the mirror and the angle of incidence was set to 30 degrees. At this point a complete set of scatter data was collected. The angle of incidence was then reset to 45 degrees and the corresponding scatter measurements were again recorded. A new point of incidence was then selected and the procedure again repeated. This is continued until the data collected is deemed sufficient. It should be pointed out that the absolute accuracy with which a given incident angle can be set is no better than 1 arc minute. However, once set, that angle can be repeatedly reset with an accuracy of 2 arc seconds. This degree of repeatability in incident angle is considerably better than the typical 3μm error associated with the accuracy to which a particular point on the mirror's surface can be relocated.

Experimental Specifics: For mirror #449, experimental scatter data was recorded at the incident angles of 30 and 45 degrees at three different points of incidence. These points of incidence will be identified as location 1, location 2, and location 3. Location 1 was set approximately at the mirror's center. Location 2 was approximately 1 mm to the left of location 1 (observers left as facing the mirror) and location 3 approximately 1 mm to the right of location 1. The measured scatter field spanned a range of about 3400 arc minutes ($\pm$ 1700 arc minutes about the normal). The scatterometer was that as described in the report previously mentioned with the exception of the detector assembly being replaced with a commercial photometer. (SPECTRA, Model 1980A). This photometer was located such that its objective lens was 3.96 m away from the mirror surface with its field of view set at the 2 arc minute setting. The analog output from this set was recorded and hand digitized so that a sampled data point was produced at angular intervals of 680 arc seconds. The fact that the field of view of the photometer exceeds 680 are seconds is not thought to be a problem because the data was observed to be highly repeatable. Thus even though this situtation would give rise to some spatial averaging, the variations in this average, in going from point to point, would still represent the form of the actual scatter field.

Results: Figures 2, 3, and 4 are logarithmetic polar plots of the scatter field intensity at locations 1, 2, and 3 respectively.

SCATTER DIAGRAM

Relative Intensity vs Spatial Angle

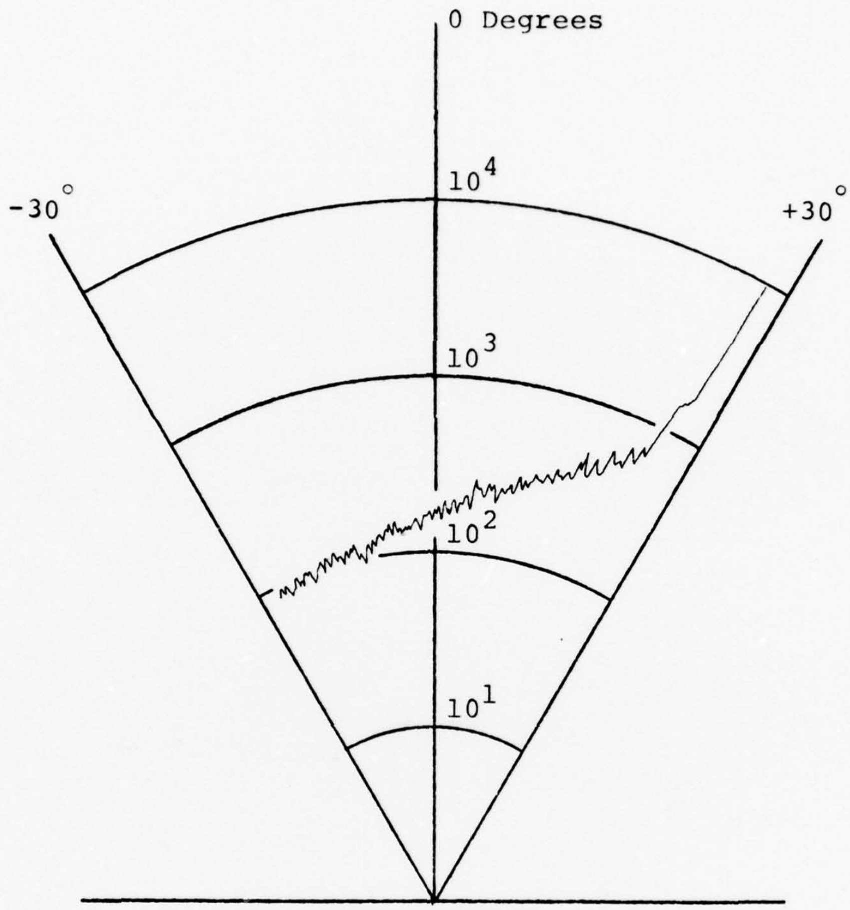

Figure 2. Plot of relative scatter intensity for mirror #449. Point of incidence at location 1. Angle of incidence = 30 degrees.

SCATTER DIAGRAM

Relative Intensity vs Spatial Angle

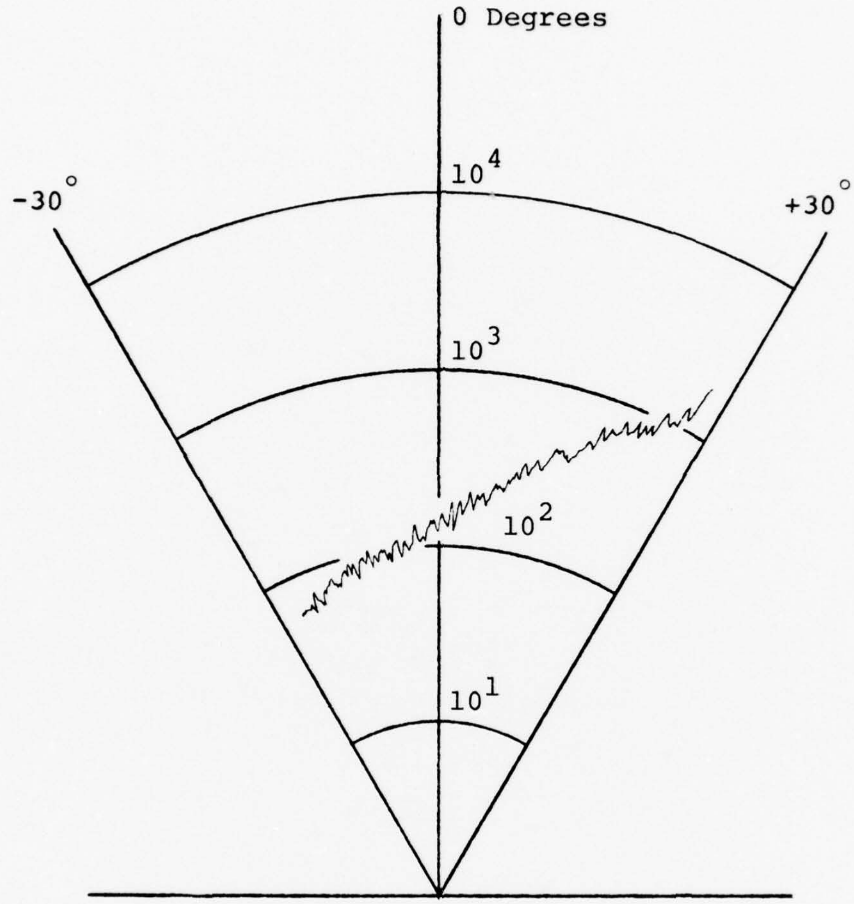

Figure 3. Plot of relative scatter intensity for mirror #449. Point of incidence at location 2. Angle of incidence = 30 degrees.

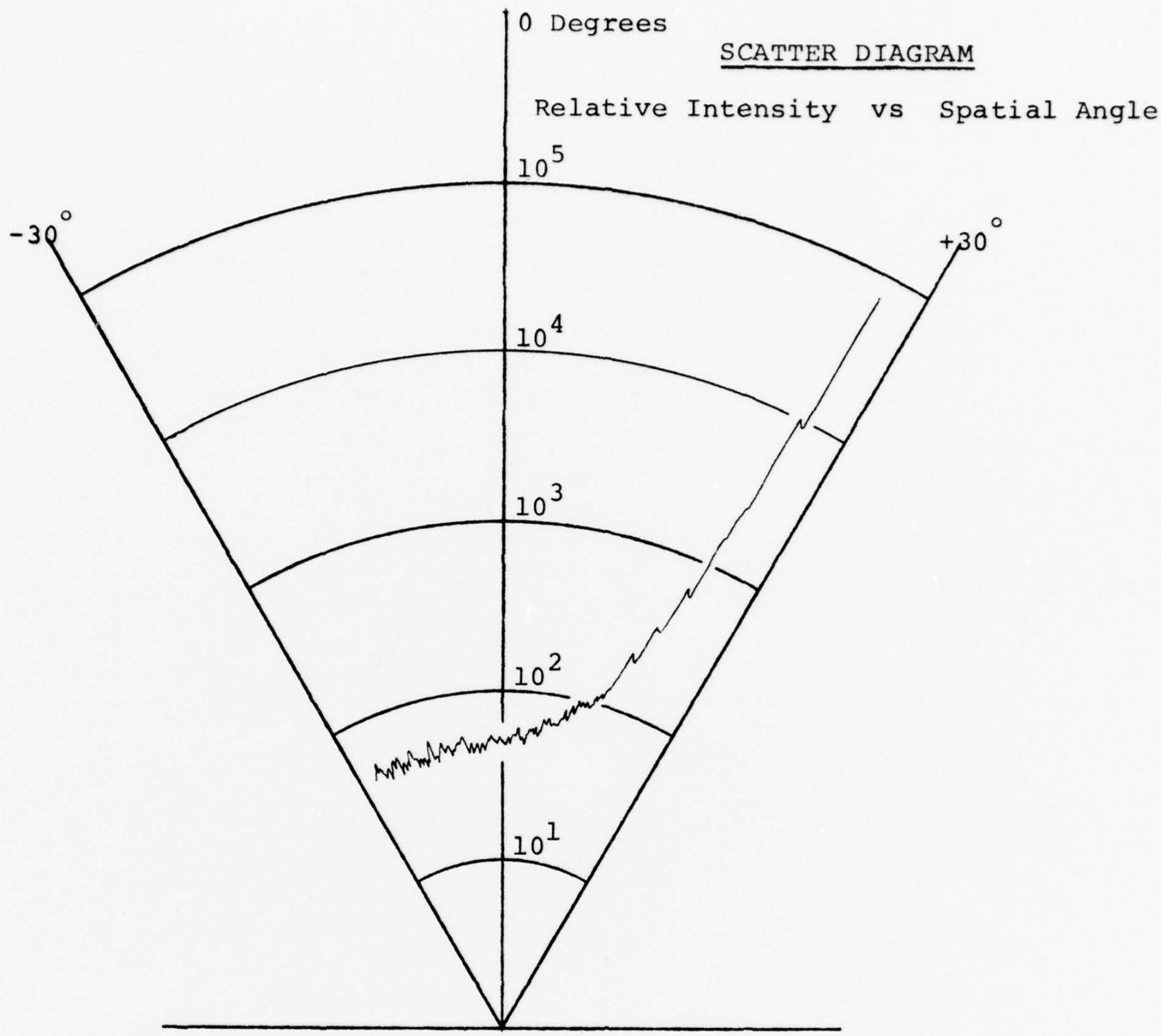

Figure 4. Plot of relative scatter intensity for mirror #449. Point of incidence at location 3. Angle of incidence = 30 degrees.

The angle of incidence for the plots is 30 degrees. A close inspection shows the following features:

1) The fine structure of the scatter field appears to be a random spatial function.
2) The normalized power in the scatter field appears to be slightly higher at locations 1 and 2 as compared to location 3.
3) The scatter field intensity, as a general trend, decreases as one moves from the reflected beam to the incoming beam. An alternate way of saying this is that over comparable spatial regions there is less energy in the back-scatter than in the forward-scatter field.

The results obtained when the incident angle was changed to 45 degrees are shown in figures 5, 6, and 7. These figures correspond respectively to locations 1, 2, and 3. Comparing corresponding 30 degree incidence and 45 degree incidence plots reveal the following:

1) The randomness of the fine structure of the scatter-field does not appear to be a function of the incident angle.
2) Normalized power in the respective scatter fields does not appear to be significantly different. (Less than a factor of 2).
3) However, the scatter intensity in the 45 degree incidence case appears to be rather uniformily spatially distributed.

SCATTER DIAGRAM

Relative Intensity vs Spatial Angle

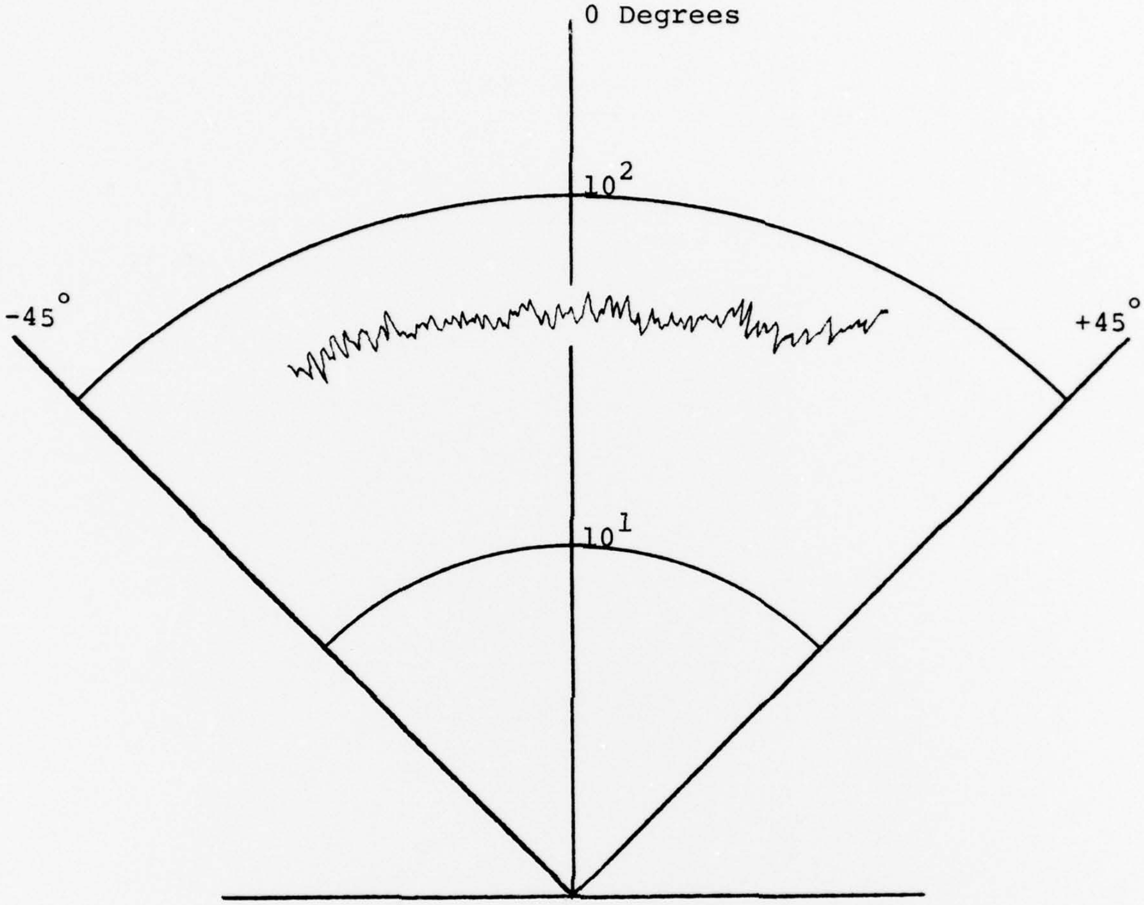

Figure 5. Plot of relative scatter intensity for mirror #449. Point of incidence at location 1. Angle of incidence = 45 degrees.

SCATTER DIAGRAM

Relative Intensity vs Spatial Angle

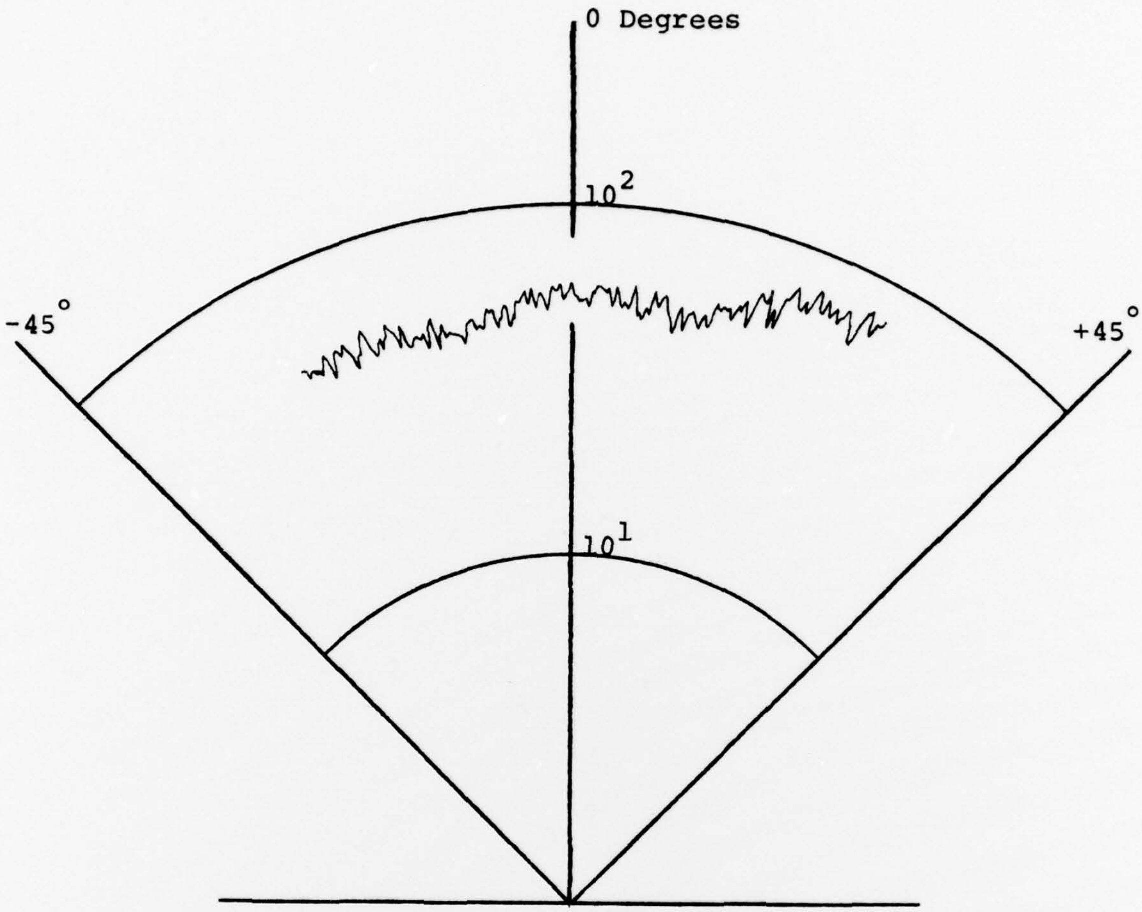

Figure 6. Plot of relative scatter intensity for mirror #449. Point of incidence at location 2. Angle of incidence = 45 degrees.

SCATTER DIAGRAM

Relative Intensity vs Spatial Angle

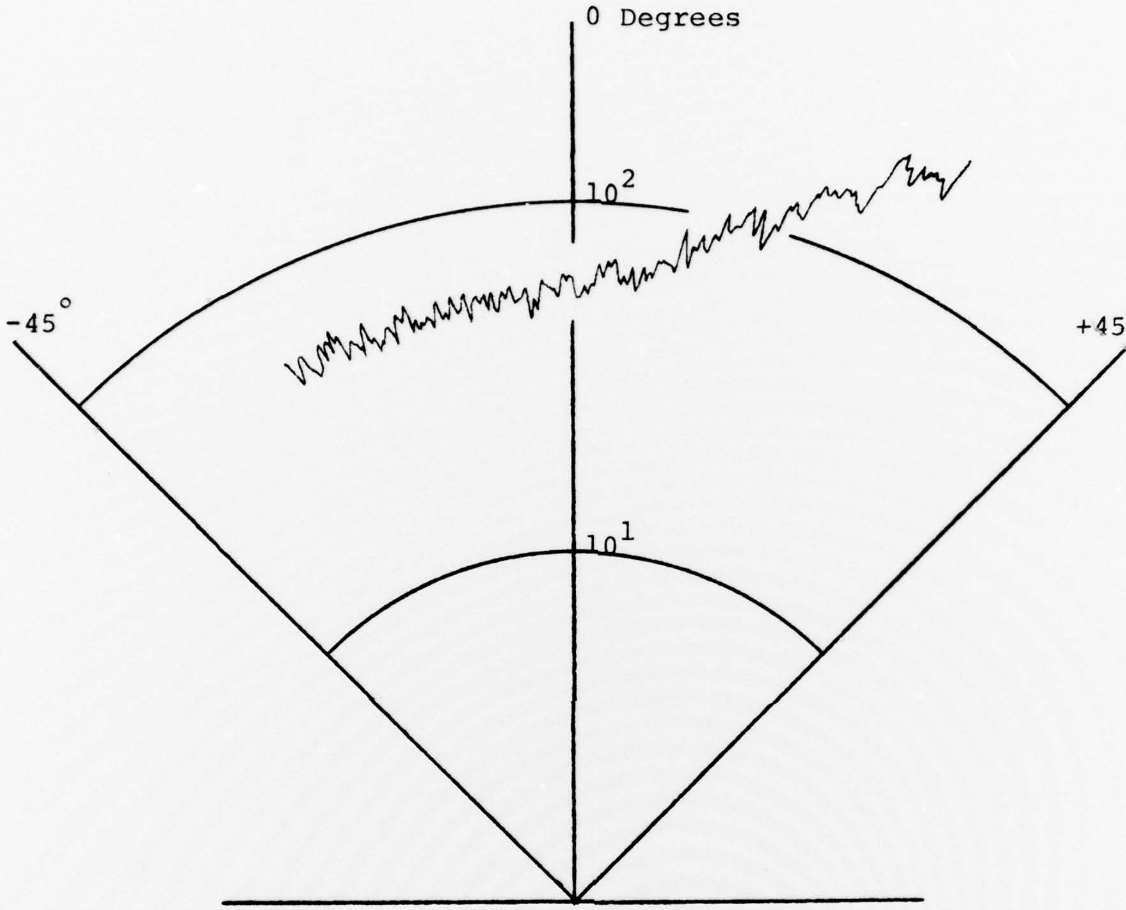

Figure 7. Plot of relative scatter intensity for mirror #449. Point of incidence at location 3. Angle of incidence = 45 degrees.

These results and comparisons suggest the following possibility. A measure of a mirror's quality may be had by comparing the character of the back-scatter to that of the forward-scatter field in a given pattern measurement. In particular, the optimum point and angle of incidence for a given mirror, is that which not only minimizes the total power in the scatter field but also tends to consentrate that power in the forward direction. This notion is somewhat supported by noting that the mirror tested was specified as a 30 degree mirror and thus as expected the 30 degree results demonstrates this property of forward scatter where as the 45 degree results do not. Also, based on the above criteria, location 3 would appear to be superior to location 1 or 2. The scatter results at location 3 even at the 45 degree angle give rise to the same conclusion.

Summary and Recommendations: The results of this research effort can be summarized as follows. The most effective technique for evaluation of scatter data produced by the dynamic scatterometer appears to be processing it so as to produce a direct polar plot. To this extent, a FORTRAN program which does this has been written, checked, and used to process scatter data. The results of processing scatter data from a test mirror are: 1) no direct evidence can be found to support the notion that lobes are present in the scatter field and 2) a measure of mirror quality may be had by comparison of the back-scatter and the forward-scatter intensities. It is suggested that a further study into this possible measure of quality be undertaken in the near future. The reason for not suggesting this as an immediate follow-up is equipment to provide for automatic mass data acquisition has yet to be brought on-line. As a further recommendation, it is suggested that at this point in the evaluation of the potential of the dynamic scatterometer, all raw scatter data be recorded in a way that is retrievable at various times in the future. This would allow the flexability necessary if one is to be able to follow up on additional processing ideas. Also this would provide the source for a comprehensive data base which yet needs to be developed. Along these lines, a good and recommended storage medium is ½ inch, 9 track, IBM compatable magnetic tape.

Acknowledgements: I would like to acknowledge the support of

Dr. W. Kent Stowell and his personnel in the Ring Laser Laboratory at WPAFB. Their cooperation in providing the scatter data used in this research made this study possible. In addition their helpful discussions and general willingness to be of service is not only here acknowledged but also deeply appreciated.

APPENDIX

FORTRAN LISTING OF PROGRAM USED FOR SCATTER DATA PROCESSING

The complete program that was used to process the scatter data described in this report is listed in this appendix. The programming language used for this program is FORTRAN IV. The various subroutines used for producing the polar plot of the results are contained in the IBM system 360 computational library at Texas A & I University, Kingsville, Texas.

The required input data set for this program is punched on standard 80 column IBM cards and consists of two cards and the measured scatter data. The first card is simply a title card which normally contains information identifying the scatter data set. This card may contain any alpha-numeric information desired and is read according to a 20A4 format. The second card contains the values for the following variables in the order given. These variables are: 1) NN - the number of samples in the data set, 2) NMAX - the number of spatial samples between the start of the data set and the normal to the mirror (not including the normal if data is sampled at that location), 3) NDEL - the angular distance between adjacent samples specified in arc seconds, 4) JL - a flag denoting if the scatter intensities are to be converted to logarithmetic values (JL $\neq$ 0 if this is desired), 5) JP - a flag denoting if a polar plot of the processed data is desired (JP $\neq$ 0 if this is desired), 6) AINC - the value of the incident angle specified in degrees,

7) XSC - the scatter data multiplying constant which is used to scale the scatter data, 8) XPS - a constant used to scale the polar plots, 9) XMAX - the upper allowable value for each data value, 10) XMIN - the lower allowable value for each data value, and 11) XRAT - the magnitude with which adjacent data values can be allowed to differ. These values are punched on the second card according to a (5I5,2F10.0,1F5.0,3E10.2) format. The scatter data, which follows, is read according to a (15F5.0) format.

```
      DIMENSION Q(20), X(1000), YP(1000), XP(1000), PHI(1000)
    1 FORMAT (1H1)
    2 FORMAT (1H1,20A4,////,1H0,1X,23HNUMBER OF DATA POINTS =,1I5,/,1H0,
     11X,20HANGLE OF INCIDENCE =,1F6.2,8H DEGREES,/,1H0,1X,14HDATA SCAN
     2FROM,1F6.2,11H DEGREES TO,1F7.2,8H DEGREES,/,1H0,1X,48HANGULAR INC
     3REMENT BETWEEN ADJACENT DATA POINTS =,1I5,12H ARC SECONDS,///)
    3 FORMAT (1H0,17X,11HDATA ERRORS,/,1H+,17X,11(1H_),/,1H0,1X,9HPOINT
     1NO.,5X,10HDATA VALUE,4X,15HCORRECTED VALUE,/,1H+,1X,9(1H_),5X,10(1
     2H_),4X,15(1H_),/)
    4 FORMAT (1H0,1X,18HNUMBER OF ERRORS =,1I6,///)
    5 FORMAT (1H0,30X,12HSCATTER DATA,/,1H+,30X,12(1H_),/,1H0,13X,17HPOL
     1AR COORDINATES,12X,23HRECTANGULAR COORDINATES,/,1H+,13X,17(1H_),12
     2X,23(1H_),/,1H0,1X,5HPOINT,4X,5HANGLE,7X,9HMAGNITUDE,13X,1HY,17X,1
     3HX)
    6 FORMAT (1H ,8X,9H(DEGREES),3(1X,17H(RELATIVE VALUES)),/)
    7 FORMAT (1H ,8X,9H(DEGREES),3(3X,13H(LOG BASE 10),2X),/)
    8 FORMAT (1H ,1I4,1F11.2,3(5X,1P1E11.3,2X))
    9 FORMAT (1H ,1I4,1F11.2,3(5X,1F9.3,4X))
   10 FORMAT (1H ,1I7,1P2E17.2)
   11 FORMAT (1H1,5I5,2F10.0,1F5.0,3E10.2)
   12 FORMAT (20A4)
   13 FORMAT (5I5,2F10.0,1F5.0,3E10.2)
   14 FORMAT (15F5.0)
      PI = 3.1415927
      RAD = PI/180.0
      NOE = 0
   15 READ (5,12) (Q(L),  L=1,20)
      READ (5,13) NN,NMAX,NDEL,JL,JP,AINC,XSC,XPS,XMAX,XMIN,XRAT
      READ (5,14) (X(I),  I=1,NN)
      WRITE (6,11) NN,NMAX,NDEL,JL,JP,AINC,XSC,XPS,XMAX,XMIN,XRAT
      DO 16 I=1,NN
      X(I) = X(I)*XSC
   16 CONTINUE
      NANG = NMAX*NDEL
      DO 17 J=1,NN
      ANG = NANG
      PHI(J) = ANG/3600.0
      NANG = NANG - NDEL
   17 CONTINUE
      WRITE (6,2) (Q(L),  L=1,20), NN, AINC, PHI(1), PHI(NN), NDEL
      WRITE (6,3)
      NMO = NN - 1
      DO 21 K=2,NMO
      XX = X(K)
      IF(XMAX-XX)20,20,18
   18 IF(XX-XMIN)20,20,19
   19 AVX = ABS(X(K)-X(K-1))
      IF(XRAT-AVX)20,20,21
   20 X(K) = (X(K-1) + X(K+1))/2.0
      NOE = NOE + 1
      WRITE (6,10) K, XX, X(K)
   21 CONTINUE
      WRITE (6,4) NOE
      WRITE (6,5)
      IF(JL)22,24,22
   22 WRITE (6,7)
      DO 23 I=1,NN
      X(I) = ALOG10(X(I))
      XMP = X(I)
      ARG = RAD*PHI(I)
```

```
      YP(I) = XMP*COS(ARG)
      XP(I) = XMP*SIN(ARG)
      WRITE (6,9) I, PHI(I), X(I), YP(I), XP(I)
   23 CONTINUE
      GO TO 26
   24 WRITE (6,6)
      DO 25 I=1,NN
      XMP = X(I)
      ARG = RAD*PHI(I)
      YP(I) = XMP*COS(ARG)
      XP(I) = XMP*SIN(ARG)
      WRITE (6,8) I, PHI(I), X(I), YP(I), XP(I)
   25 CONTINUE
   26 IF(JP)27,28,27
   27 CALL XPLOT(NN,YP,XP,AINC,XPS)
   28 WRITE (6,1)
      STOP
      END
```

```
      SUBROUTINE XPLOT(NN,YP,XP,AINC,XPS)
      DIMENSION YP(1), XP(1)
      DO 1 I=1,NN
      YP(I) = XPS*YP(I)
      XP(I) = XPS*XP(I)
    1 CONTINUE
      CALL PLOTS
      CALL PLOT (4.0,4.0,-3)
      CALL SYMBOL (0.0,0.0,0.04,3,0.0,-1)
      CALL SYMBOL (0.0,6.0,0.04,3,0.0,-1)
      XXX = XP(1)
      YYY = YP(1)
      CALL PLOT (XXX,YYY,3)
      CALL PLOT (XXX,YYY,2)
      DO 2 L=2,NN
      XXX = XP(L)
      YYY = YP(L)
      CALL PLOT (XXX,YYY,1)
    2 CONTINUE
      CALL PLOT (4.5,-4.0,-3)
      CALL PLOT (0.0,0.0,999)
      RETURN
      END
```

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REPORT DOCUMENTATION PAGE

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A study and development of data processing techniques for spatial scatter intensity data from a MLD mirror was undertaken. Several processing schemes were investigated with the result that processing the data so as to produce a true and scaled polar plot of the scatter field seems to be the optimum way of displaying the information.

Studies of the scatter field of a particular MLD mirror → next page

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did not support the notion that lobes are to be found in the pattern. On the contrary, the scatter field is more accurately described as a random spatial function. In addition, studies of the processed data patterns suggests that a possible measure of mirror quality may be had by direct comparison of its forward and back scatter characteristics.